

Borehole Seismic Monitoring of CO2 Injection in a Diatomite Reservoir

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Background

A subsurface CO2 injection pilot program is currently being operated by Chevron USA Production Company in the Lost Hills, California oil field (Figure 1). This pilot program, which is partially funded by the U.S. Department of Energy (DOE) as an enhanced oil recovery project, is ideally suited for design and testing of geologic sequestration concepts including subsurface monitoring techniques. Our goal is to demonstrate through field testing techniques for imaging subsurface CO2 and for monitoring geologic sequestration. Other investigators are studying electromagnetic (EM) and electrical methods and we plan to integrate the geophysical results.

CO2 has been used by the oil industry for many years to enhance oil production. Previous studies in carbonate reservoirs have shown that seismic velocity changes are caused by CO2 injection and that these changes can be spatially mapped using crosswell seismic surveys (Wang, et al., 1998). The seismic velocity change can be up to 10% which is easily detectable and mappable with modern crosswell seismic surveys. Therefore, borehole seismic surveys hold great promise for mapping and long term monitoring of sequestered CO2.

The quantity and quality of CO2 sequestration will, of course, vary greatly depending of the reservoir properties. The diatomite reservoirs of central California have unusually high porosity (>50%) and low permeability (<1 millidarcy). Because of the low permeability, the diatomite reservoir is developed with 1.25 acre well spacing. Despite this small well spacing, only 5% of the estimated 2.2 billion barrels of oil in place has been produced since discovery in 1910.

The composition of the diatomite at Lost Hills is approximately equal parts biogenic silica, clay and siltstone. As the diatomite is buried at higher pressures and temperatures, the silica, which is initially in a form called opal-A, has a phase transition to opal-CT and then to quartz. Hydrocarbons are found in all three phases with enhanced production from fracturing in transition zones. Depositional laminations in the diatomite with varying silica content affect the system permeability. The layers with phase transitions can have enhanced natural fracturing and therefore higher effective permeability, while other layers, with lower permeability can be flow barriers.

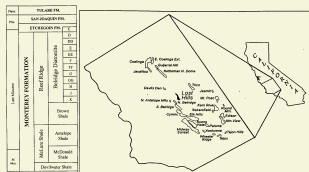


Figure 1. Geologic Column (left) and nearby oilfield locations (right) for the Lost Hills field from Chevron USA.

Chevron Lost Hills CO2 Injection Monitoring - Field Site



Photo 1. On-site CO2 storage tanks. Four trucks per day are used to refill tanks with CO2 from a Chevron refinery.

Field Site and CO2 Injection Information

The CO2 injection being operated by Chevron USA in their Lost Hills field. There are four injection wells in a 1.25 acre grid (centered in the blue squares in Figure 2). The reservoir volume around one injection well (11-BWR) is being monitored by crosswell seismic studies using two observation wells (OB-C1 and OB-C2). The reservoir depth is about 425 m (1400 ft) to 640 m (2100 ft) below ground level. The injection well was hydraulically fractured over the reservoir interval prior to injection. This part of the Lost Hills field has also had previous enhanced production using water flood.

The CO2 injection began in August 2000 at a relatively low flow rate of 125 million cubic feet (Mcf) per day. The rate has been gradually increased to the current rate of 425 Mcf/day per injection well. The injection pressure is held at 800-900 psi. The reservoir temperature is about 108 °F. At this pressure and temperature, the CO2 is expected to be in gas phase. The expected effect of the CO2 to lower reservoir fluid viscosity is shown in Figure 3. A tracer has been placed in the CO2 and to date (in the early stages of injection) about 1.2% of the tracer has been detected in production wells. The CO2 is being transferred from Chevron E1 Second, California refinery using 4 trucks per day to supply this 4 well injection program. The CO2 is stored locally in tanks (Photo 1.) and distributed to the injection wells with surface pipes (photo 2).

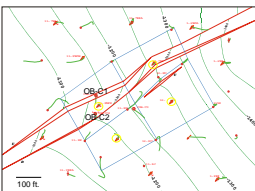


Figure 2. CO2 Injection site (blue lines) with contoured top of reservoir (green lines) and interpreted faults (red lines). Our study is in wells OB-C1 and OB-C2 for injector 11-BWR. Each blue square contains one of the four CO2 injection wells (yellow circles). This is a 1.25 acre pattern. Figure from M. Mones (Chevron, USA).



Photo 2. CO2 distribution plumbing (background) with observation well OB-C1 (foreground).

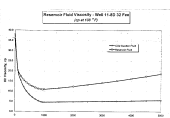


Figure 3. Viscosity of reservoir fluid before and after CO2 injections. The large drop in viscosity at the pressures expected in the reservoir (800-900 psi) demonstrates an expected benefit of mobility and production (from Chevron, USA).

Seismic Properties of CO2

The seismic properties of CO2 (velocity and density) vary with pressure and temperature. In particular, the transition from liquid phase to gas phase has a dramatic effect on seismic properties as shown in Figure 4 from Wang, et al., 1999. This is a key point at the Lost Hills site where the injection is at 800 to 900 psi and temperature is about 108 °F, so we expect the CO2 to have a subsurface gas phase. If there is a subsurface gas phase, the seismic visibility and mappability will be greatly enhanced. Previous crosswell and anglewell seismic studies have shown the ability to detect a single gas-bearing fracture such as the CO2 filled hydrofracture at Lost Hills (Majer, et al., 1997).

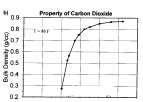
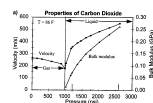


Figure 4. Effect of CO2 on seismic P-wave velocity (top, a) and bulk density (bottom, b). From Wang, et al., 1999.

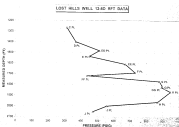


Figure 5. Reservoir pressure in various diatomite intervals at Lost Hills. From Chevron USA.

Borehole Seismic Acquisition

LBL has collected three borehole seismic data sets using the observation wells OB-C1 and OB-C2. Two crosswell surveys used OB-C1 for a source well and OB-C2 for a receiver well (see Figure 2). The first survey used a piezoelectric source while the second used an orbital vibrator source and both used 3-component well-logging accelerometer sensors. The third survey was a singlewell imaging experiment (i.e. source and receivers in the same well) in OB-C1 using the piezoelectric source and both the 3-component accelerometers and hydrophone sensors. The surveys had 0.1 (1.5 m) interval spacing between source and receiver depths. The distance between wells is approximately 80 ft (24 m). The piezoelectric crosswell survey obtained high frequency data (>2000 Hz) giving wavelengths of about 1 m. A 3-component receiver gather is shown in Figure 7. This data set is notable for being narrow banded. Spectral analysis (Figure 8) shows narrow spectral peaks at about 1500, 1700 and 2200 Hz. One implication is a 'narrow' waveform which has been previously observed in diatomite studies (Witt, et al., 1997). The spectral content and amplitude also vary with depth as shown in Figure 9 and this may represent material property variations within the diatomite laminations.

The orbital vibrator source is lower frequency (70-350 Hz) providing a separate scale of investigation (wavelengths of about 6 m). The orbital vibrator is a recently developed borehole source and is notable for generating two components of source motion, inline and cross-line, and thereby generating both P- and S-waves (Daley and Cox, 2000). The measurement of P- and S-wave velocities allows greater understanding of subsurface material properties, especially in gas and liquid saturated porous material. Figure 6 shows a 6-component receiver gather for the orbital vibrator data (2-components of source and 3-components of receiver). The wellfield shows P-waves generated by the in-line source and a combination of S-wave and tube-wave energy generated by both sources. We believe the slow S-velocity in the diatomite allows generation of a 'Mud' wave, i.e. a formation shear-wave generated by the borehole tube-wave.

In general, the diatomite has a fairly complicated seismic wave propagation due to the high porosity and mixed pore fluid (oil, water and gas). The detection and delineation of CO2 will be combined with understanding the overall wave propagation properties of diatomite.



Photo 3. Observation wells used for seismic crosswell. Well C2 had seismic sensors and Well C1 had seismic sources.

Acknowledgments

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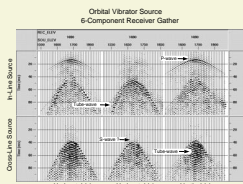


Figure 6. 6-component data from orbital vibrator source (2-components) and 3-component receivers. P-waves and tube-waves are strong. S-wave is inferred from travel time.

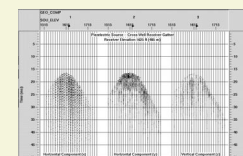


Figure 7. Piezoelectric source data for 3-component sensor. A strong P-wave arrival is observed.

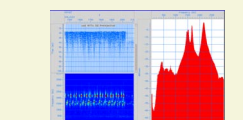


Figure 8. Spectral analysis of piezoelectric source data for zero offset propagation. Seismograms (top left), frequency vs depth (bottom left) and total frequency content (right) are shown.

References

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Current Results

We have obtained preliminary 2-D tomographic images of velocity for both projection seismic crosswell experiments. These results are shown in Figures 9 and 11 with an interpreted cross section provided by Chevron USA in Figure 10. The high frequency piezoelectric data set has higher resolution, as expected. A low velocity zone is seen in Figure 11 between 1600 and 1700 ft. The apparent dip of this zone may be indicating the faulted offset seen in the cross-section. Lower velocities are measured from the longer wavelength orbital vibrator data (figure 9) which may be an indication of different scales of heterogeneity being measured in the diatomite. It is not unusual to see frequency dependent measurements of seismic velocity. No sonic logs are yet available in these wells, however sonic logs, which are about 10,000 Hz, often have higher velocities than surface seismic data which are about 100 Hz. Borehole tomography falls in between these scales of measurement.

The most important aspect of these data sets is that they represent a baseline measurement of reservoir properties before CO2 injection. The complexities of the diatomite reservoir make direct measurement of one property (such as CO2 concentration) very difficult. However, time-lapse changes measured against this baseline survey, should be controlled by CO2 injection and flow properties. The post-injection surveys should begin in spring of 2001. It is the time-lapse changes in seismic properties which should be most useful in monitoring and mapping CO2 in the subsurface.

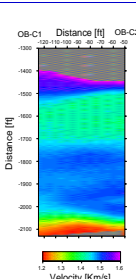


Figure 9. Velocity tomogram for orbital vibrator source P-wave.

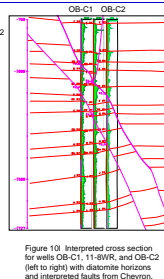


Figure 10. Interpreted cross section for wells OB-C1, 11-BWR, and OB-C2 (left to right) with diatomite horizons and interpreted faults from Chevron, USA. Depths are below sea level, add 400 ft to compare with tomograms.

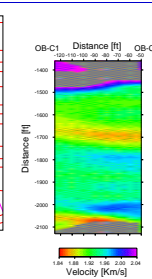


Figure 11. Velocity tomogram for piezoelectric source P-wave.